Nonlinear and Dissipation Characteristics of Ocesan Surface Waves in Estuarine Environments

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LONG-TERM GOALS

The overall goal of this work is the development of computational modules for the dissipation of surface wave energy due to expanses of bottom mud and marshland vegetation. The computational modules would represent both the dissipative effects on the surface waves and the effects of dissipation on other processes of wave transformation and evolution, with particular attention paid to the nonlinear energy exchange among wave frequencies. In addition these modules would allow for feedback between the surface wave and the energy dissipating feature.

OBJECTIVES

1) Develop processes models of the physics of dissipation in estuarine areas.

2) Use optimized ensemble simulations to represent effects of dissipation on wave processes.

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3) Develop and test low-dimension, reduced representations of estuarine effects for inclusion into operational wave models.

4) Develop experimental versions of operational wave models.

APPROACH

We will first work to develop computational models for detailed, phase-resolved predictions of wave dissipation in estuarine areas. These models will include various mud proxy models (viscous fluid, viscoelastic semi-rigid bed, Bingham plastic) for wave/mud interaction and mud-induced dissipation. These proxy models for mud dissipation have fairly broad-banded responses over a large swath of wave frequencies, so they can be expected to inhibit various nonlinear interactions in the random wave field. The task here will be to surmise whether this frequency dependence is scalable or self-similar over a range of frequencies, conditions or proxies. In addition the feedback between surface and lutocline waves will be investigated to determine whether or not these interactions have an effect on surface wave energy; allowing for surface-lutocline interaction can potentially *redirect* surface wave energy rather than sinply dissipate it. A similar line of inquiry will be performed for wave-vegetation interaction, though the expected parameter space for this phenomena may be significantly reduced compared to mud dissipation. These models will be validated with available data.

To make this suitable for a random wave spectral model (as most operational wave models are), we must find ways of randomizing our results with the deterministic models. One possible method would be the use of a neural network approach, which uses data from the models to establish a “training set” which helps predicts future behavior. The neural network mapping strategy of Krasnopolsky et al. (2002) will be one candidate for use; it was used for the Wavewatch-III © model, and should be available for use here.

In addition, and in concert with the project “Development of Numerical 3-Wave Interactions Module for Operational Wave Forecasts in Intermediate-Depth and Shallow Water” (PI: Sheremet; co-PI: Kaihatu) we will investigate physically-justifiable reduced dimension models which will retain the dominant components of wave-mud-vegetation interaction but will also allow for more expedient calculation.

Finally we will make use of the models developed above to create experimental versions of operational models. This will allow us to test the physics in the developed models while using the general framework of operational wave models. We will conduct robustness tests of the system to determine the conditions under which the new models exhibit sub-optimal behavior. We will also work with the NCEP and NAVO (if available) operational forecasters, as well as the scientific community at the Naval Research Laboratory (NRL) and Engineering Research and Development Center (ERDC) to insure smooth incorporation of these developments into their operational run stream.

The TAMU team consists of the PI (Kaihatu) and a Ph.D. student, Mr. Navid Tahvildari, who is developing models and analysis for investigating the interactions between surface and interfacial waves, as well as investigating the sensitivity of wave processes to mud properties and wave-current interaction effects on damping by mud. The UF team consists of Alex Sheremet (PI), Miao Tian and Cihan Sahin (Ph.D. students) who are working on modeling nonlinear wave evolution in dissipative environments (mud), and the response of sea bed to wave action.

WORK COMPLETED

Several models have been recently developed. The stochastic nonlinear wave propagation (Agnon and Sheremet, 1997) was tested on field observations collected during the 2008 and 2010 field experiments (e.g., Safak et al., 2010; Sheremet et al., 2010; Sahin et al., submitted a; Sahin et al., submitted b). A typical bed evolution cycle has been identified and studied in detail (e.g., Sahin et al., submitted b, see next section). A deterministic frequency domain model which couples wave-current interaction with mud dissipation was also developed and tested on laboratory data (Kaihatu and Tahvildari, submitted). A model which looks critically at the stability and resonant interactions between the lutocline wave and the surface wave for fluids with two different densities has been developed (Tahvildari and Kaihatu, submitted) and is presently being extended to include surface-surface and interface-interface near-resonant interactions as well. This stability model focuses on the growth of the interface wave in time. To look at general spatial evolution characteristics, a parabolic model for nonlinear evolution of resonant and near-resonant triads in space is presently under development.

RESULTS

In this section we discuss results on several areas of the project:

Bed Evolution: Figure 1 shows the detailed bed evolution as recorded by PC-ADP backscatter intensity at a platform near the 4-m isobath. Under energetic waves, the stiff bed softens, liquefies, expands, and mixes with water. The mobilized surficial layer of sediment is then rapidly resuspended by near-bed turbulence (a burst-like process), significantly increasing the suspended sediment concentration in the entire water column. In turn, increased SSC-induced stratification acts as a negative feedback that controls the further development of the process by dampening near-bed turbulence and suppressing mixing (Safak et al., 2010; Sahin et al., submitted a). As the storm wanes, decaying near-bed turbulence allows the suspended sediment to settle, leading to the formation of fluid-mud layers (Safak et al., 2010; Sheremet et al., 2010). Eventually, through dewatering and consolidation, the stiff bed state is reached again.

Wave-bed coupling: An examination of the vertical structure of the flow velocity indicates that a surficial bed layer as thick as 20 to 30 cm oscillates with the waves (maximum RMS horizontal velocity observed during the most active period is of the order of 20 cm/s) while also sliding downslope with a mean velocity of the order of 5 cm/s (similar to that observed by Jaramillo et al. (2008). The fact that wave-induced oscillations of the bed (which in turn contribute to wave dissipation) are associated with high-density mud layers suggests that complex, nonlinear mud rheologies (visco-elastic/plastic or Bingham type) should play a role in modeling wave-bed interaction (mud-induced wave dissipation, and wave-induced bed-reworking).

Wave dissipation mechanisms: An inverse modeling approach of Rogers and Holland (2009), modified for using a nonlinear wave model that accounts for triad interaction (Agnon and Sheremet, 1997) was used to investigate the constituents of the observed net wave dissipation (Sheremet et al., 2010). The results (Figure 2) confirm that the dominant wave dissipation mechanism is wave-bottom interaction, and that the process is triggered by the reworking of bed sediment by waves. Wave dissipation typically increases during a storm, as the bed is softened by waves and sediment is re-suspended. The maximum of mud-induced dissipation (about 50% loss of incoming energy flux loss over approx. 4-km propagation distance) is attained typically at the end of the storm, when the bed sediment in a soft, under-consolidated state, likely close to gelling.

Nonlinear three-wave interactions play a crucial role in the interpretation of the frequency distribution of net wave dissipation (Figure 2). The contribution of the nonlinear interactions is expressed in transfers from the peak of the spectrum toward higher and lower frequencies, resulting in a increased apparent dissipation of the spectral peak and net growth in the high and low frequency bands. This trend is not captured by the linear model, which suggests that neglecting the effect of nonlinearities can lead to aliasing nonlinear energy transfers into dissipation effects, distorting the representation of mud-induced dissipation.

Combined mud-induced dissipation and wave-current interaction: It has been shown that nonlinear interactions in shallow water random waves are suppressed in opposing currents and enhanced in following currents (Kaihatu 2009). When mud-induced dissipation is added, it is seen that this damping effect is stronger in opposing currents than in following currents. Figure 3 shows model results of wave spectra (Figures 3a, 3b) and evolution of the energy density of the spectral peak and several harmonics (Figures 3c-3f) for waves propagating over highly viscous mud. Two different lengths of mud patch are used to investigate potential spectral energy equilibration and rebound in the lee of the mud patch due to triad nonlinearity. It is found that, despite the strong damping for the longest mud patch (Figure 3e, 3f), energy at the second and third harmonics of the spectral peak do gain in energy in the area beyond the mud patch. This demonstrates the robustness of triad nonlinear interactions to equilibrate energy in the spectra even after drastic energy damping via mud dissipation. Additionally, it is apparent that the dissipation of the higher harmonics of the spectral peak is greater with the opposing currents.

Resonant interactions between surface and interface waves: In order to move away from the restrictive one-way influence of mud on surface waves, we developed evolution equations for the interactions of the surface waves with waves on a fluid interface. This is cast in the framework of the Boussinesq equations for shallow water, and affords us a straightforward way to include viscous damping in the lower layer and, furthermore, determine the resulting effect on nonlinear interactions. Hydrodynamic stability analysis (Drazin and Reid 1981) was first applied to the two-layer Boussinesq equations in order to determine the growth rate of the interface waves, both for inviscid flow and the case of a weakly viscous bottom layer. Figure 4 shows the growth rate for the case of exact resonance between this triad. In order to address how robust the interaction is in the face of other nonlinear processes, we have also included surface wave-surface wave interactions and interface wave-interface wave interactions, both of which are nearly resonant. Preliminary results show very strong growth rates of the interface wave for particular choices of interacting frequencies.

IMPACT/APPLICATIONS

Much of the present and near-future Navy capability on predicting regional and nearshore processes assumes a sandy (non-cohesive) sedimentary environment. The present research enhances this capability by providing field data essential for model validations and by identifying processes and developing mechanisms which allow expansion into areas with significantly different characteristics. One of the direct implications of the present research is the developing the foundation for the development of a coupled hydrodynamic-seafloor prediction model for muddy environments.

RELATED PROJECTS

This research benefits from, and enhances, parallel research (Sheremet) funded by ONR Littoral Geosciences & Optics Program to develop sediment transport forecasting capabilities for muddy beaches.

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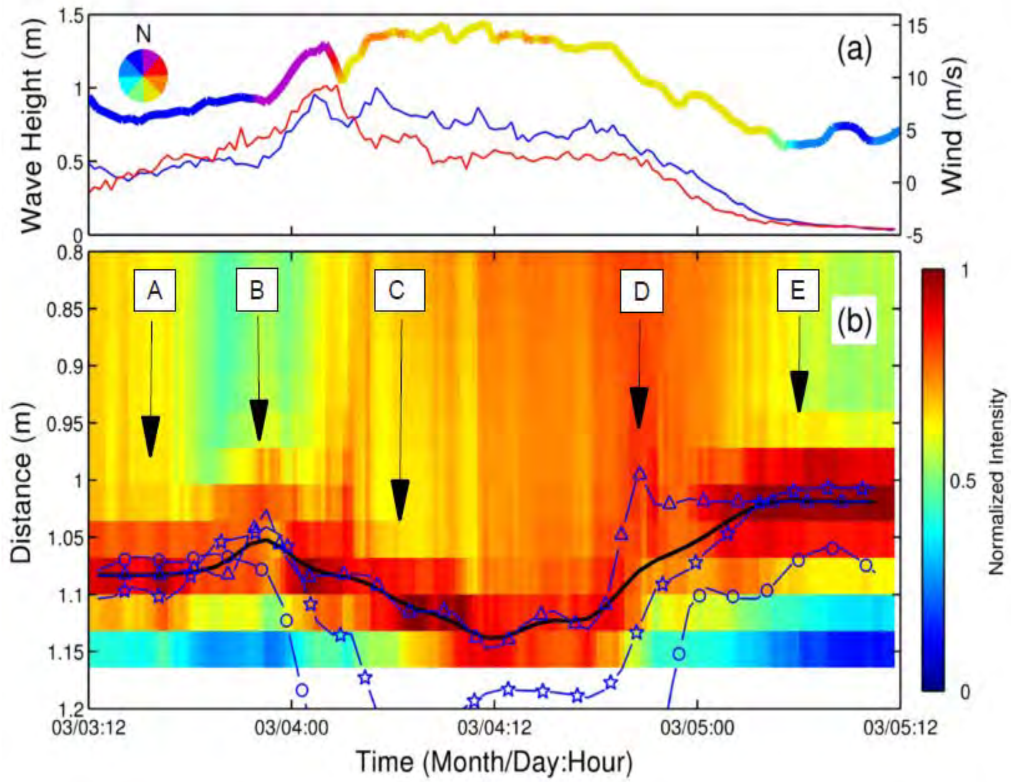

Figure 1:Analysis of PC-ADP backscatter showing a 20-30-cm thick surficial layer of the bed oscillating and sliding down-slope during the storm. a) Significant wave height (blue: short waves, red: swell); and wind speed and direction (color code indicated the direction the wind blows toward). b) Normalized PC-ADP backscatter intensity. The lines represent the location of: maximum backscatter intensity (triangles); zero mean horizontal velocity (stars), and zero RMS horizontal velocity (circles). The continuous thick line is a smoothed estimate of the bed position. A surficial bed layer of approximately 20-30 cm oscillates with the waves and slides down-slope. Arrows mark the hypothesized stages of bed evolution: (A) solid bed; (B) breaking of the bed matrix and water absorption (liquefaction/fluidization/expansion); (C) bed erosion; (D) settling and bed accretion; (E) formation of fluid muds. The process is followed by eventual de-watering/consolidation (not shown).

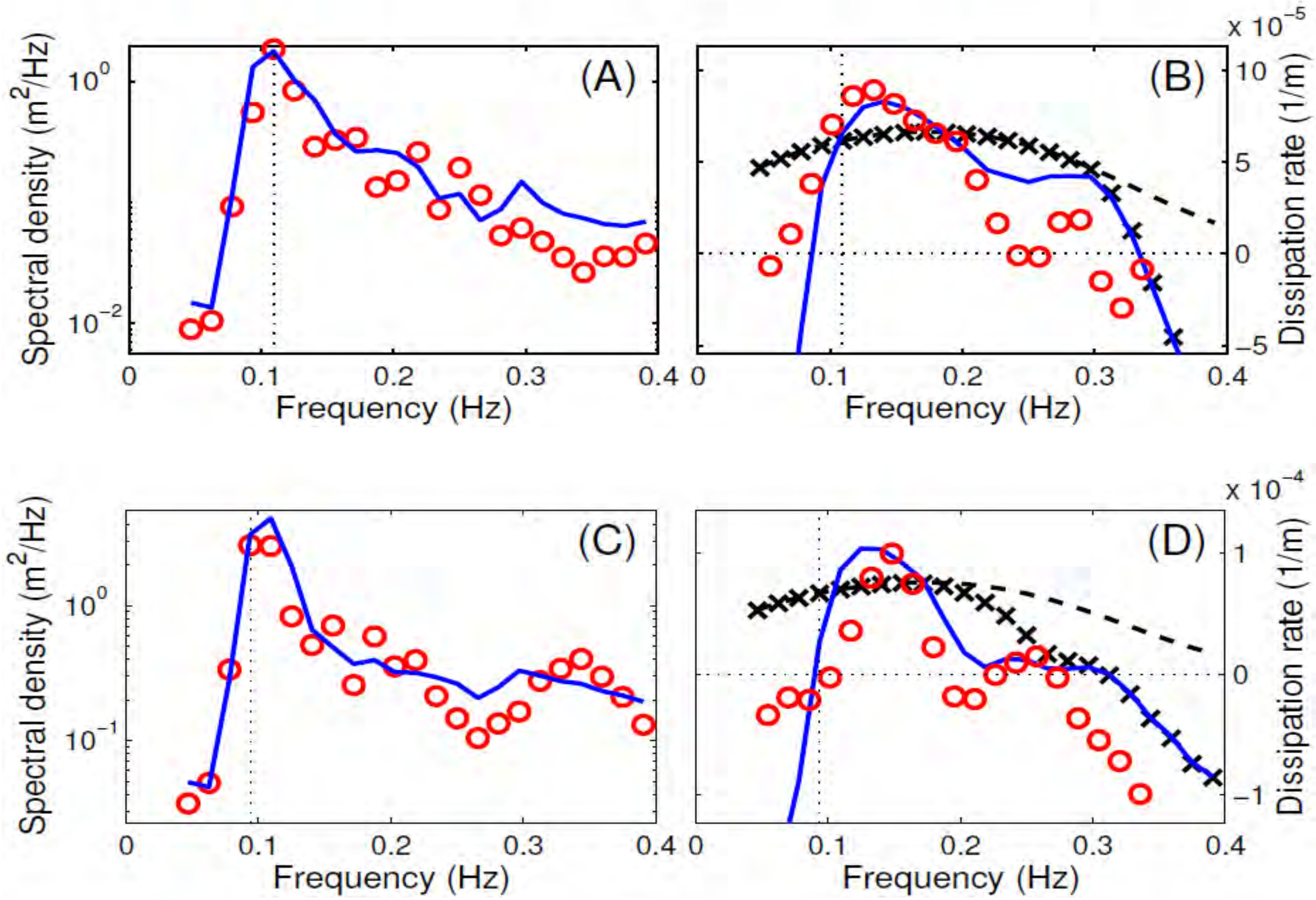

Figure 2 : Example of numerical simulations of wave spectrum evolution (A,C) and dissipation rates (B,D) for the storm of March 10-11th 2006 (red -- observations; blue -- model; black dashed -- mud-induced dissipation rate, Ng, 2000; crosses -- net "linear" dissipation rate, including wind input, whitecapping, and mud-induced dissipation). The nonlinear transfer of energy from the peak toward higher and lower frequencies appears to increase the net dissipation of the spectral peak and results in net growth rates for higher and lower frequency bands. Nonlinear wave-wave interaction conserves energy, therefore it does not contribute to the bulk (frequency integrated) wave dissipation/growth.

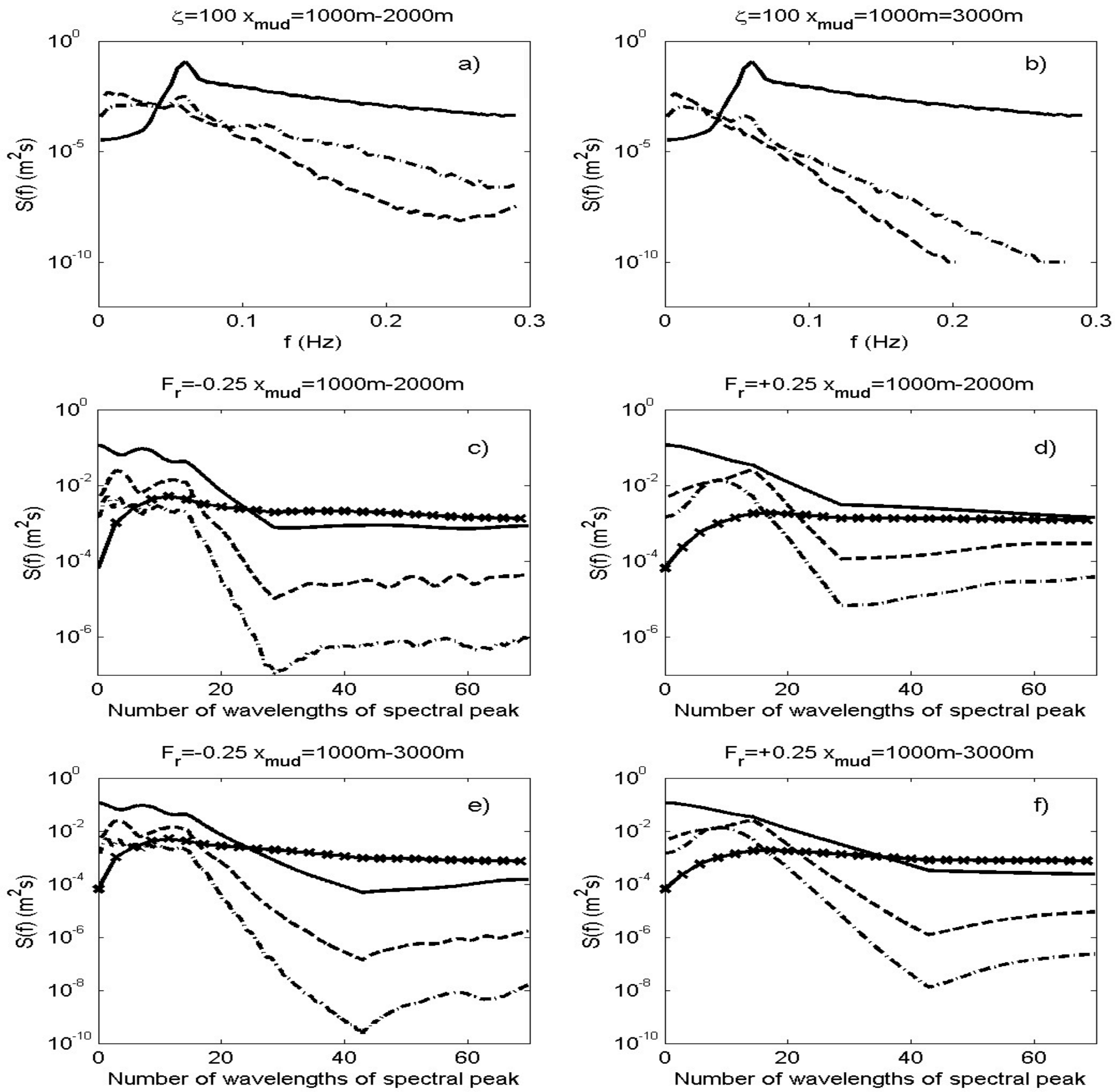

Figure 3: Wave spectra and evolution of harmonics from nonlinear wave-current-mud model. Top row: wave spectra for a) x_{mud}=1000m – 2000m and b) x_{mud}=1000m – 3000m. For a) and b), solid line is spectrum at x=0, dashed line is spectra at downwave end of mud patch with opposing current, and dash-dot line is spectra at downwave edge of mud patch with following current. Middle and bottom rows: spectral energy density at several frequencies evolving over distance for: c) opposing current, x_{mud}=1000m – 2000m; d) following current, x_{mud}=1000m - 2000m; e) opposing current, x_{mud}=1000m – 3000m; and f) following current, x_{mud}=1000m – 3000m. For c) through f): Energy density at spectral peak f_p=0.0625Hz (solid line); second harmonic of peak (dashed line); third harmonic of peak (dash-dot line) and subharmonic of peak (f_p/2; dash-x).

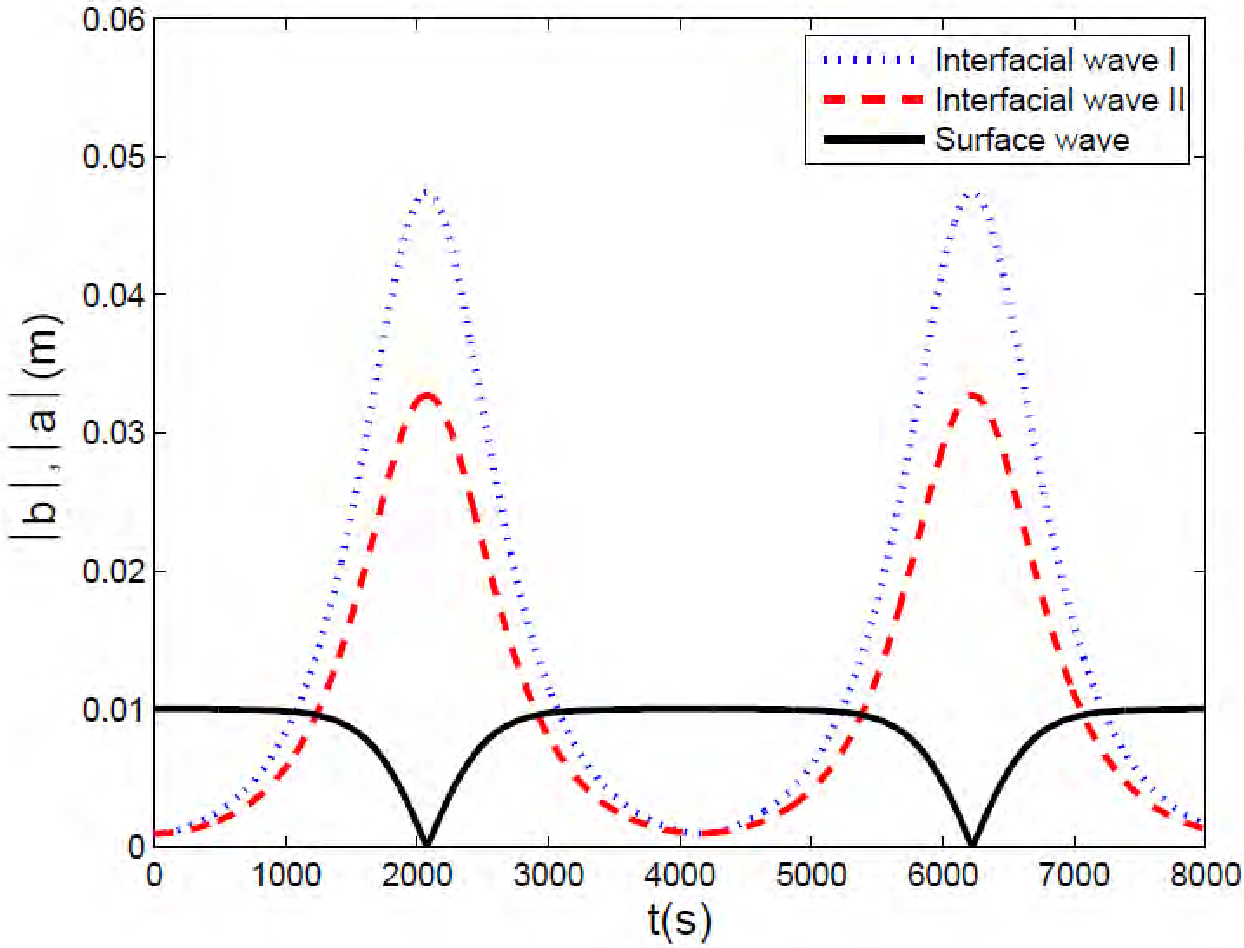

Figure 4. Temporal variation of dimensionless amplitudes of interacting surface and interfacial modes: Upper layer depth is 0.8m, lower layer depth is 0.2m, bottom layer is 1.07 times as dense as the upper layer. Interface waves propagate at a 70^oangle to the surface wave.